Lessons learnt from the application of a multi-variable controller for nitrogen removal in the Mekolalde wastewater treatment plant: good simulation practices in control

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ABSTRACT

Although often perceived as tools for use by scientists, mathematical modelling and simulation become indispensable when control engineers have to design controllers for real-life wastewater treatment plants (WWTPs). Nonetheless, the design of effective controllers in the wastewater domain using simulations requires effects, such as the nonlinearity of actuators, the time response of sensors, plant model uncertainties, etc. to have been reproduced beforehand. Otherwise, control solutions verified by simulation can completely underperform under real conditions. This study demonstrates that, when all the above effects are included at the outset, a systematic use of simulations guarantees high quality controllers in a relatively short period of time. The above is exemplified through the Mekolalde WWTP, where a comprehensive simulation study was conducted in order to develop a control product for nitrogen removal. Since its activation in May 2011, the designed controller has been permanently working in the plant which, from this time onwards, has experienced significant improvements in the quality of water discharges combined with a lower utilization of electricity for wastewater treatment.
Key words | activated sludge, automatic control, mathematical modelling, simulation, wastewater

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INTRODUCTION

Located in the region of Guipúzcoa (northern Spain), the Mekolalde wastewater treatment plant (WWTP) was designed and constructed in 2005 to serve a total population of about 50,000 inhabitants. With capacity to process up to 10,000 m^3 of pre-treated wastewater every day, a conventional activated sludge configuration was adopted to deal with nitrogen removal requirements. From its start-up in June 2008 until April 2011 the only operative controllers in the secondary treatment have been, as in many other plants, those related to low-level operations such as regulating (1) the internal recycling flow-rate, (2) the surplus sludge flow-rate, and (3) the concentration of dissolved oxygen (DO) in the aerated basins. The plant was equipped with advanced on-line instrumentation for suspended solids (MLSS), nitrates (NO_3-N) and ammonia (NH_4-N); however, their use was confined to merely assisting the decisions taken by plant operators. Figure 1 illustrates the plant-layout of the secondary treatment, with sensors and actuators also included.

In 2009 and under the acronym ADD-CONTROL, a 2-year European research project was launched with the aim of producing new specific simulation software (henceforth, Add-Control software) totally oriented to ensuring a rapid and reliable development of control products for WWTPs (Brockmann *et al.* 2011; Maiza *et al.* 2011). Nevertheless, prior this project, it is the paper published by Prieto & Irizar (2009) that first introduces the modelling principles on which the three-layer software architecture of Add-Control later relies. When compared to similar simulation tools, a significant feature of Add-Control is the provision of a library of components to reproduce the real behaviour of sensors and actuators most typically found in real WWTPs. In particular, Amerling *et al.* (2012) give a detailed description of the model equations implemented in this library in order to realistically predict the energy consumed by pumping operations in WWTPs.

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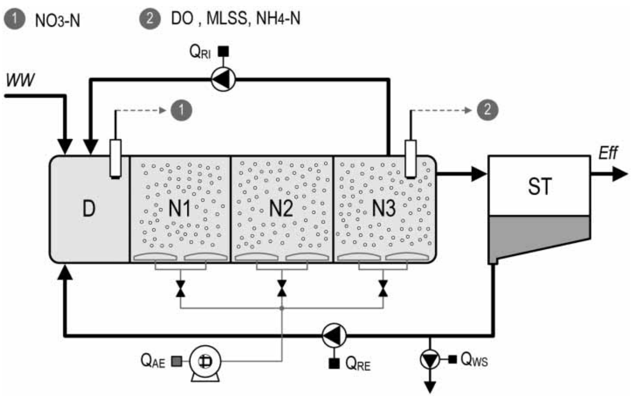


Figure 1 | The Mekolalde WWTP: plant-layout of the secondary treatment.

The connection between the ADD-CONTROL project and the Mekolalde WWTP comes from the fact that, out of the activities included in this project, the validation of the performance of the new software in a real case-scenario was addressed in this plant. Unlike the aforementioned papers covering mathematical modelling and programming issues connected with Add-Control software, this study deals with its practical value, which is exemplified through its contribution to the realization of a multivariable control product aimed at optimizing nitrogen removal in the Mekolalde WWTP. To this end, this study has been organized into two main sections. First, all the modelling and simulation procedures that were followed during the design of the control product will be thoroughly explained. Following this, the second section will focus on analyzing the performance values of the Mekolalde WWTP before and after the operation of this controller. It should be noted that the methodological work described above is in part a replication of that reported by Ayesa *et al.* (2006) when the Galindo-Bilbao WWTP was successfully provided with automatic controllers. Nonetheless, during this replication, special consideration has been given to refining the design methodology, the ultimate goal being to shorten the total time invested to complete the control solution.

CONTROLLER DESIGN USING SIMULATIONS

The software Add-Control and, specifically, its comprehensive library of models for treatment units, real sensors, real actuators, controllers, etc. was used to easily build a plant simulator for secondary treatment in the Mekolalde WWTP. Intrinsic to Add-Control, the plant simulator followed a three-layer implementation where each layer was devoted to mimicking tanks and reactors (wrapped in the so-called 'mass' bottom layer), sensors and actuators ('instrumentation & actuation' intermediate layer), and controller devices ('automation & control' top layer) respectively. Figure 2 shows a Matlab/Simulink®-based implementation of the simulation tool where each block corresponds to each of the above three layers. Specifically for the mass layer, the standard ASM1 model was adopted to predict biochemical transformations (Henze *et al.* 2000).

Model calibration

Once the plant simulator for Mekolalde was completed, data on the performance of the plant in 2009–10 were collected in order to proceed with its calibration. The latter involved not only assigning appropriate values to the coefficients of the biochemical model but also to the parameters of the models associated with real sensors and actuators. Moreover, special interest was taken in predicting the consumption of energy by (1) the air blowers and (2) the internal recirculation pumps. With one of the beauties of automatic control being its ability to save energy, the design of control products using specifications of energy reduction at the outset of the simulation study becomes *de facto* imperative. Nonetheless, unlike other simulation studies in which fine predictions are highly recommended, in this work calibration tried to reach trade-offs between model accuracy and the time required to complete the process. Accordingly, apart from those data contained in the historical database of the plant, no other information was used to calibrate the model. In particular, available information included the following: (1) laboratory-analysis data

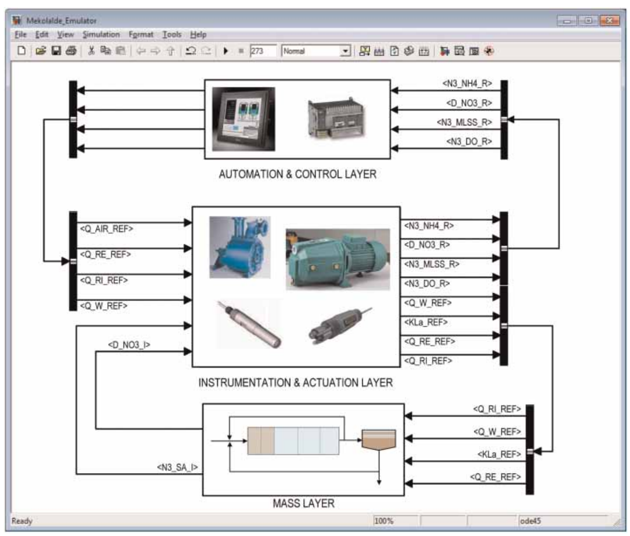


Figure 2 | Plant simulator for the Mekolalde WWTP.

of total suspended solids, volatile suspended solids, total chemical oxygen demand (COD), filtered COD, total Kjeldahl nitrogen (TKN), NH_4-N and NO_3-N corresponding to daily composite samples from both the wastewater and the treated effluent; and (2) data from online instrumentation, namely: flow-rate of pumps, MLSS, NH_4-N and DO in the last aerated tank, and NO_3-N and temperature in the anoxic tank.

In compliance with modern control design, the calibration conducted in this study sought to specify, rather than fixed values for the model coefficients, the uncertainty region in which model predictions were reasonably acceptable. As usual, the calibration process started by characterizing wastewater composition for the medium- and long-term variations of MLSS in the biological tanks to be reproduced using the plant simulator. Figure 3 shows the quality of predictions for 9 months of plant performance characterized by a gradual decrease of MLSS from 5,000 to 2,500 mg/L. Once the mass of solids was correctly simulated, calibration goals then focused on the adjustment of the kinetic coefficients in order to predict the observations of NH_4-N and NO_3-N in the effluent of the plant. To this end, uniform and uncorrelated probability distributions were defined *a priori* for six kinetic coefficients directly linked to the removal of nitrogen (Table 1).

Using the Latin hypercube sampling (LHS) technique, 5,000 random samples from the six-dimensional uncertainty space were generated to run 5,000 simulations where the effluent results for each run were compared to the respective real observations. Out of the total samples, less than 250 achieved satisfactory predictions and were, as a result, finally selected. The simulation results corresponding to one of these samples are illustrated in Figure 4. A statistical analysis of the selected samples was carried out to determine the uncertainty for the six kinetic coefficients shown in Table 1 after model calibration. From this analysis, two major conclusions were drawn: (1) the marginal probability distributions for each kinetic coefficient did not have a uniform shape, on the contrary they were close to normal; and (2) these coefficients exhibited non linear correlations.

The observed correlations involved using dimensionality reduction techniques to infer a new uncertainty space made up of uncorrelated variables. In this regard, the first option was to resort to principal component analysis (PCA) (Jolliffe 1986) but, being based on linear algebra, this technique failed to capture the non linear relationships in our data. This problem was overcome by breaking down the non-linear uncertainty into several linear data subsets and subsequently applying PCA individually to each subset. This was actually done by making use of clustering methods to find each

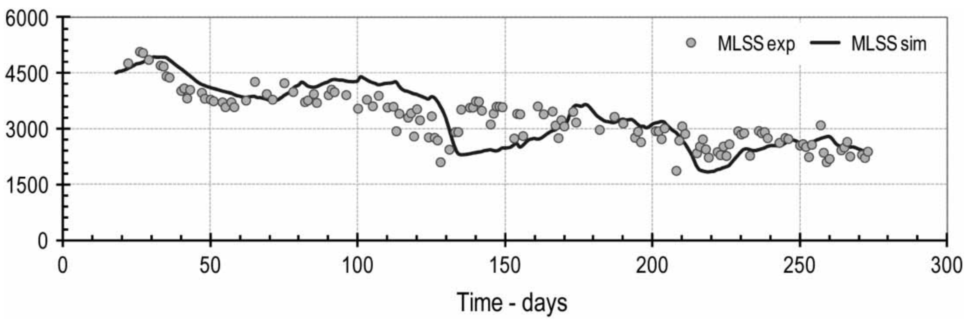
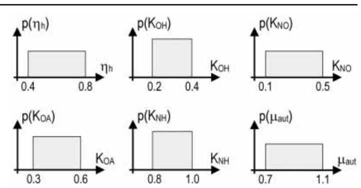


Figure 3 | Period from July 2009 to March 2010: daily average values for MLSS in Mekolalde; comparison between real and simulated data.

Table 1 | *A priori* model uncertainty: uniform probability distributions between Min and Max values

Coefficient	Unit	Min	Max
η_h	–	0.4	0.8
K_{OH}	mg O_2/L	0.2	0.4
K_{NO}	mg NO_3-N/L	0.1	0.5
K_{OA}	mg O_2/L	0.3	0.6
K_{NH}	mg NH_4-N/L	0.8	1.00
μ_{aut}	d^{-1}	0.7	1.1



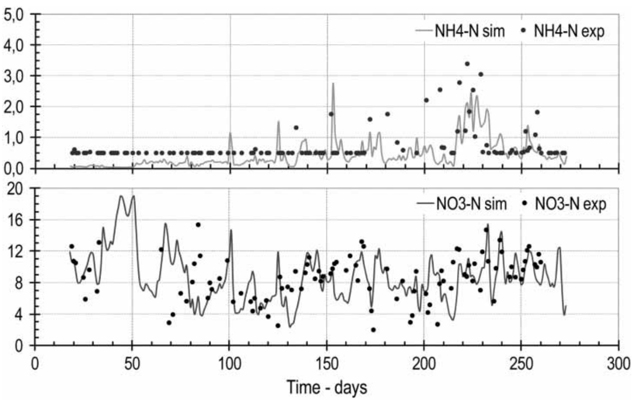


Figure 4 | Period from July 2009 to March 2010: daily average values for effluent NH_4-N and NO_3-N in Mekolalde; comparison between real and simulated data after calibration.

linear subset. The reason for the latter was supported by the evidence of successful studies on the application of clustering algorithms to piecewise linearization of nonlinear functions (Ferrari-Trecate *et al*. 2003; Ghosh *et al*. 2011). Table 2 gives the final results of the uncertainty ranges for each kinetic coefficient. It can be seen that, unlike Table 1, in this case uncertainty did not follow uniform distributions. In this regard, the generation of random samples from the final uncertainty space involved this two-step procedure:

1. Random samples were generated applying LHS to the principal components of each subspace.
2. Each sample was projected back into the original 6-dimensional space using the PCA loading matrix of the subspace it belonged to.

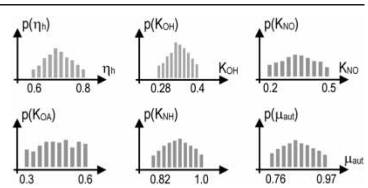
Controller design

Contained in the control layer, a control solution made up of three non-interacting proportional-integral-derivative (PID) controllers was integrated into the plant simulator. While this control scheme (Figure 5) can be clearly recognised amongst the vast literature dedicated to automatic control of activated sludge systems (Amand *et al*. 2013; Olsson 2012), it was the manner used to tackle the design of each PID that introduced some differentiation compared to similar studies on the topic. Specifically, the parameters of the NH_4-N controller were tuned only after the non linear characteristic of the aeration system (Beltrán *et al*. 2013), the dynamic response of the DO sensors and the 'non-continuous' operation of the NH_4-N ammonia analyzer had been added to the problem. In doing so, it was possible to design a controller that combined proper disturbance rejection properties with minimum use of the control effort and, therefore, of the energy for aeration. Similarly for the second controller, the NO_3-N controller, design specifications gave priority to minimizing the control effort, in this case the internal recirculation flow-rate which, in addition, was limited to values in the range of 300–500 m^3/h.

Although at the beginning the third controller was specified to maintain MLSS concentrations close to a constant reference, simulations revealed that this goal demanded designs with relatively high gains mainly due to the irrelevance that energy savings had in this case (surplus sludge pumping, the control action of the MLSS controller, accounts for a very small fraction of the overall energy consumption in WWTPs). An argument to limit the control effort was however the very well-known effect that the surplus sludge flow-rate has not only on the secondary treatment (it determines the sludge retention time) but also on the sludge treatment stream (sludge load). It was seen that high-gain designs were effective at rejecting disturbances in the secondary treatment but at the expense of introducing large and undesired disturbances in the sludge treatment. The latter required a redefinition of the original control specifications; in particular, the specification for disturbance attenuation in the secondary treatment had to be relaxed. Thus, the new design tried to reach a reasonable trade-off between acceptable disturbance rejection in the secondary treatment and minimum impact on the sludge treatment. It

Table 2 | Probability distributions for the uncertain kinetic coefficients after calibration (Min and Max represent lower and upper boundaries)

Coefficient	Unit	Min	Max
η_h	–	0.6	0.8
K_{OH}	mg O_2/L	0.28	0.4
K_{NO}	mg NO_3-N/L	0.2	0.5
K_{OA}	mg O_2/L	0.3	0.6
K_{NH}	mg NH_4-N/L	0.82	1.00
μ_{aut}	d^{-1}	0.76	0.97



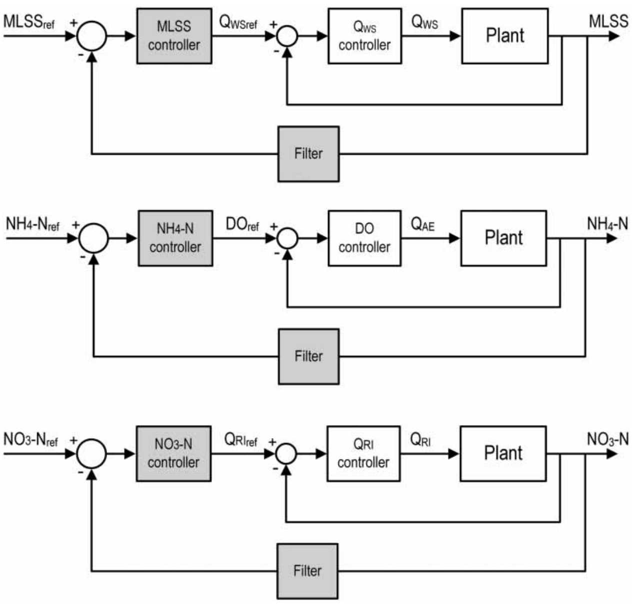


Figure 5 | Controller scheme: three single-input–single-output decentralized loops.

is worth mentioning that, in chronological order, the redesign of the MLSS controller was conducted after feedback about the real performance of the initial design was collected from the plant. In fact, the above was a confirmation that the design of control products for WWTP involves an iterative process that begins with simulations, continues with full-scale validation and often requires further simulations to refine the original control solution (Figure 6).

The same procedure was followed in the design of each individual PID controller. Steady-state simulations were performed first and the value of the proportional gain progressively increased until an acceptable trade-off between the steady-state error and the control effort was reached. Then, the integral time was tuned in order to achieve smooth adaptation of the control action to medium/long-term disturbances (weekly and seasonal variations). Moreover, the practical realization of the integral part was provided with anti-windup features. Finally, the derivative term was tuned to keep deviations of the controlled signal, caused by hourly disturbances, within acceptable levels. To be precise, the derivative term was only added in the NH_4-N and NO_3-N control algorithms, with a low-pass filter also being necessary to prevent signal noise amplification effects.

Figure 7 shows the dynamic response of the controllers after completion of the simulation-based design procedure. The anti-windup properties of the designed controllers are apparent in Figure 7 (top) through the DO controller response (the inner loop in the NH_4-N controller scheme). In addition, the disturbance response of the NH_4-N and MLSS controllers are respectively illustrated in Figure 7 (middle) and Figure 7 (bottom). As expected, while the NH_4-N controller (reference = 1 mg N/L) is able to manage hourly disturbances, the parameters of the MLSS controller (reference = 3,000 mg/L) have been intentionally adjusted to only attenuate long-term disturbances (in the range from weeks to months).

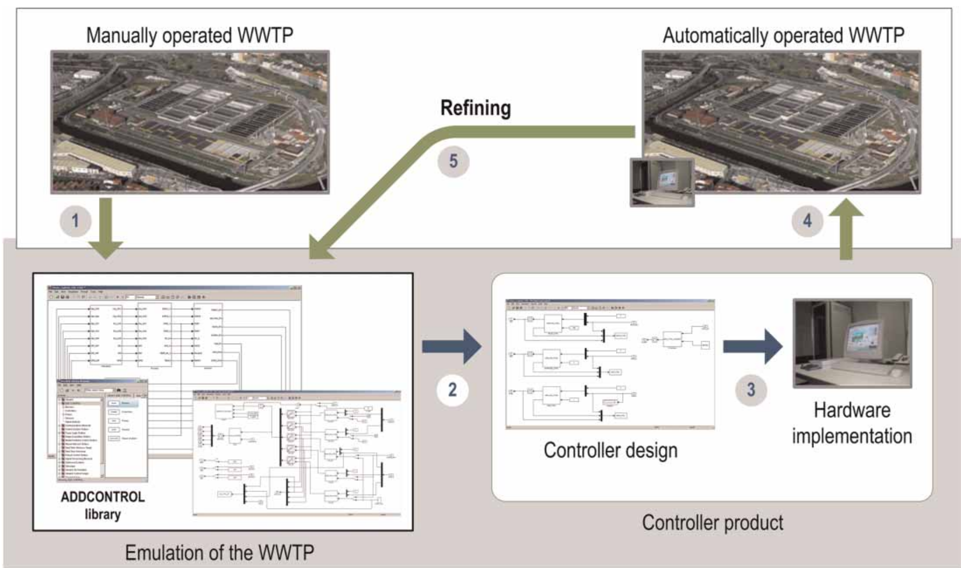


Figure 6 | Systematic procedure for design of controllers using simulations: (1) preparing the plant simulator; (2) running simulations to design and validate the controller; (3) implementing the control product: first release; (4) testing the product under real conditions; and (5) refining the control product by combining simulations with feedback on real performance.

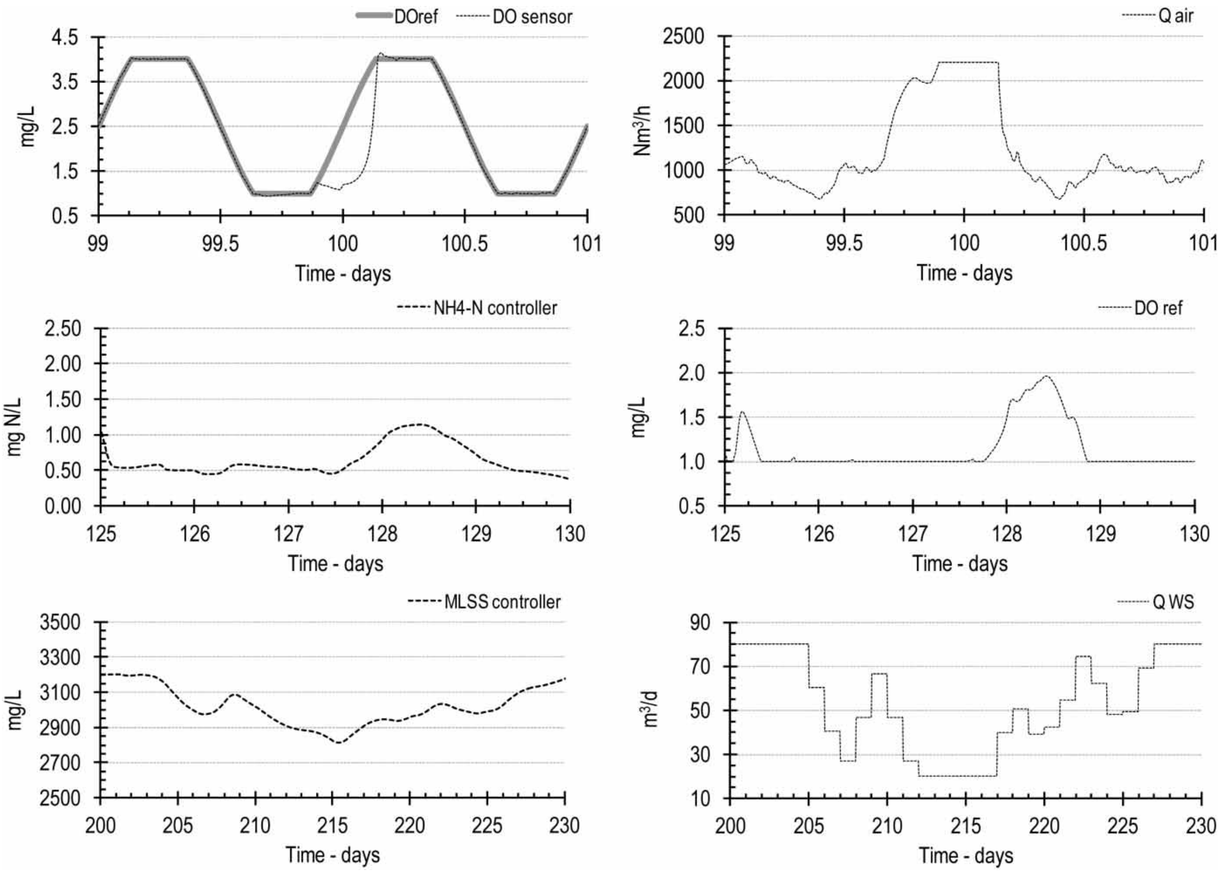


Figure 7 | Dynamic response of the control solution: (top) DO controller; (middle) NH_4-N controller; (bottom) MLSS controller.

Performance analysis of controllers

The performance of the above controllers was analyzed running random simulations over 1,000 samples taken from the uncertainty space specified after model calibration (Table 2). The results of this study are summarized in Table 3 which also includes simulation results for the conventional operation of the plant. As usual, performance results were quantified in terms of the quality of the treated effluent (total inorganic nitrogen: TIN = NH_4-N + NO_3-N) and operating costs (energy). In short, simulations proved to be useful not only for designing and tuning each controller but also for obtaining a realistic estimate of the expected improvements: by about 32% and 8% for water quality and energy savings, respectively. Although the effluent ammonia increased in controlled mode, values were compliant with requirements (daily average values below 1 mg N/L).

Table 3 | Simulation study: performance results of the Mekolalde WWTP for conventional and controlled operations

		Conventional operation	Controlled operation	Impact
NH_4-N	mg/L	0.55 (0.11)	0.84 (0.14)	Below requirements (1 mg N/L)
NO_3-N	mg/L	8.93 (0.26)	5.56 (0.28)	−38%
TIN	mg/L	9.48 (0.30)	6.40 (0.39)	−32%
Energy costs	kW	45.3 (0.2)	41.5 (0.4)	−8%

Note: Standard deviation values in parentheses.

FULL-SCALE IMPLEMENTATION OF THE CONTROL PRODUCT

In April 2011 once the simulation study had been concluded, the three controllers were implemented and put into operation at the plant. Since then, plant operation has permanently exhibited an out-performance in the same order of magnitude as that predicted by the simulation software. Figure 8, for example, gives a quantifiable view of the immediate improvements in the quality of the effluent after the activation of the designed controller. Similarly, a simple comparison of the operation of the plant in the summer season for the years 2009 and 2012 (Figure 9) clearly proves the benefits of the control solution. Whilst with the NH_4-N controller the plant was able to maintain the concentration of NH_4-N in the effluent consistently below 1 mg N/L, it was due to the combined work of the NH_4-N and NO_3-N controllers that the effluent TIN hardly ever reached values higher than 10 mg N/L. In addition, the large variations exhibited in 2009 for the total mass of suspended solids were substantially mitigated in 2012 by the action of the MLSS controller. Equal credit must be given to the superior performance of the controllers in terms of energy consumption; this can be noted in Figure 9 by simple inspection of the flow-rate profiles for the internal recycling and for the air supply.

A complementary analysis of the controller response is given in Table 4 which compares the performance of the plant month-by-month, between July and December over 2 consecutive years, 2010 (conventional operation) and 2011 (controlled operation). Some figures have been highlighted in grey boxes to signify superior performance (either in effluent quality or energy consumption). From the above figures, a substantial improvement in the quality of the effluent is clearly attributable to the action of the controllers. In particular, while in 2010 the effluent TIN

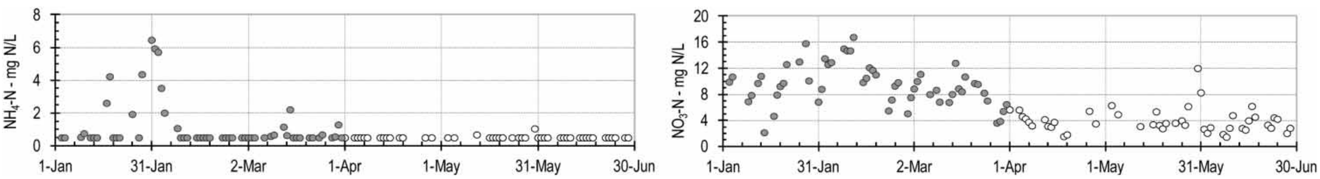


Figure 8 | Effluent quality before (grey circles) and after (white circles) the activation of the control product.

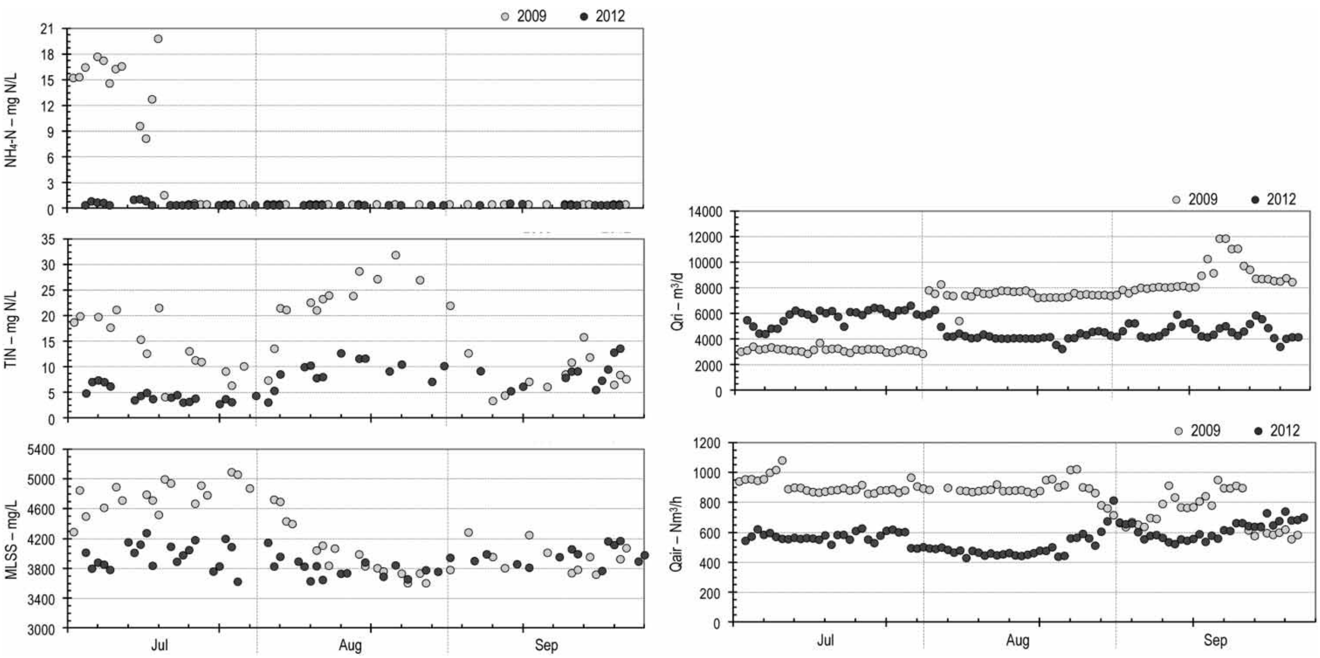


Figure 9 | Performance of the Mekolalde WWTP for the summer seasons corresponding to 2009 (the control product not installed yet) and 2012 (the control product installed and in operation).

Table 4 | Plant performance: comparative results of conventional operation (2010) versus controlled operation (2011)

		Jul		Aug		Sept		Oct		Nov		Dec	
		2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
Q_{INF}	m^3/h	116	145	108	99	130	168	140	137	207	218	178	262
Temp	°C	21	19	21	N/A	20.7	N/A	18.4	18.7	15	16.9	12.2	14.5
MLSS	mg/L	3,602	3,333	3,828	3,211	3,839	3,553	3,993	3,176	3,370	2,968	3,283	3,062
Q_{RI}	m^3/h	418	204	371	202	419	221	441	207	481	200	388	191
Q_{AE}	Nm^3/h	537	461	475	327	554	559	621	576	544	642	632	654
NH_4-N eff	mg N/L	<0.5	<0.5	0.5	<0.5	<0.5	<0.5	2.0	<0.5	6.5	<0.5	<0.5	<0.5
TIN eff	mg N/L	5.1	6.1	12.3	6.1	6.9	5.7	9.2	6.5	15.2	6.7	11.2	7.8

experienced continuous variations with values ranging from 5 to 15 mg N/L, during 2011 this process variable was consistently kept to average values of below 8 mg N/L. A concurrent reduction of the dissolved oxygen in the aerated basins (DO) and of the internal recycling flow-rate (Q_{RI}) was, in part, the cause of these positive results. Specifically, while the average DO decreased to values below 1 mg/L, Q_{RI} was reduced by about 50% when compared with the values for 2010.

A rough estimate of aeration savings was obtained by contrasting plant performances in October 2010 and 2011. These 2 months showed similar values for the influent flow-rate (Q_{INF}) and temperature (Temp), therefore providing a reasonable basis for comparison. In this regard, the air flow-rates were reduced by 7% due to the ammonia controller. This improvement was, however, far below simulated estimates (20%). Based on the assumption that measurements were reliable, the two probable determinants of such discrepancy might have been: (1) that the influent nitrogen load had been higher in October 2011 than in October 2010; and (2) that, since the effluent ammonia was higher in October 2010 (2.0 mg N/L versus <0.5 mg N/L in October 2011), nitrogen removal had been lower in that month. Finally, it was not possible to obtain direct values for energy because the plant does not have real-time power consumption meters for the internal recycling pump and for the air blower. Nonetheless considering that with the controllers the flow-rates of these two actuators decreased, it can be objectively asserted that energy consumption also experienced proportional reductions.

CONCLUSIONS

Important lessons were drawn from the full process covering the design, installation and validation of a nitrogen removal control solution for a medium-size urban WWTP. The first one is that in order to come up with a good control solution, modelling and simulation tools must be accommodated to the specific needs of control and not the contrary. The above has been exemplified through the Add-Control simulation software, whose use in this study has proven to be decisive in ensuring a reliable transition from simulation to full-scale application. The extent of model calibration when it comes to design controllers was another point discussed in this work: Is an accurate calibration of the plant model strictly necessary or it is better to combine a rough calibration with model uncertainty? In view of the results obtained the answer is that the second approach appears more suitable for this specific problem. As a matter of fact, with uncertainty being one of the *raisons d'être* of robust control, the control design procedure proposed here can be regarded as representing a modest contribution to motivate further developments on robust control in the wastewater field. Last but not least, it can be asserted that replication of the work presented in this paper in other plants is straightforward with minor adaptations. Moreover, considering that the total time invested to complete the present work was less than 1 month, it is anticipated that replication in other WWTPs could take a similar time.

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